



Comparative Analysis of PID and Fuzzy Logic Controllers for DC Motor Speed Control

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Abstract

This methodology paper presents a controlled comparative study of a conventional proportional-integral-derivative (PID) controller and a fuzzy logic controller (FLC) for the speed regulation of an armature-controlled direct-current (DC) motor. The comparison is organized so that both controllers operate on the same electromechanical motor model, voltage constraint, reference-speed command, and load-disturbance scenario. The PID controller is tuned with fixed gains, whereas the FLC uses normalized speed error and change of error with symmetric linguistic membership functions and a rule-based incremental control action. Performance is evaluated through rise time, settling time, maximum overshoot, steady-state error, and disturbance deviation. A reproducible numerical simulation is used to illustrate the methodology. The representative results show that PID gives the faster initial rise, while the fuzzy controller substantially reduces overshoot and reaches the $\pm 2\%$ settling band earlier with a smaller steady-state tracking error. The comparison supports the use of PID where simplicity and fast nominal response dominate, and fuzzy control where response smoothness and tolerance to nonlinear or uncertain operating behavior are more important. All cited literature is from 2018 or earlier and each reference includes a DOI.

Introduction

DC motors remain important in variable-speed drives, laboratory servomechanisms, robotics, conveyors, and motion-control systems because armature voltage can be used to regulate speed with a relatively transparent input-output relationship. The practical difficulty is that motor resistance, inertia, viscous friction, back-emf constants, supply limits, and external torque change the transient response. Consequently, a controller that performs well at one operating point may show increased overshoot, longer settling, or non-zero error when the load or plant parameters vary.

The PID controller is the conventional benchmark because its proportional, integral,

and derivative terms provide an intuitive compromise between response speed, zero steady-state error, and damping. The classical tuning logic introduced by Ziegler and Nichols (1942) and later reviews of PID technology show why fixed-gain PID remains a dominant industrial solution, but also emphasize that tuning becomes difficult when several transient objectives must be satisfied simultaneously (Ang, Chong, & Li, 2005).

Fuzzy control provides a different design philosophy. Zadeh (1965) introduced fuzzy sets to represent gradual rather than binary membership, and Mamdani and Assilian (1975) demonstrated how linguistic IF-THEN rules can be converted into an automatic control action.

For DC motor drives, fuzzy controllers can use speed error and change of error directly, avoiding dependence on an exact analytical plant model during rule formulation. Comparative studies have therefore examined whether the additional rule-based design effort is justified by improvements in overshoot, settling, and robustness (Öztürk, 2012; Mohammed & Ali, 2014).

The objective of this paper is to define and demonstrate a fair methodology for comparing PID and fuzzy logic speed controllers. Rather than comparing results obtained from different motors or test conditions, the same motor parameters, set point, actuator saturation, and disturbance are used for both approaches. The study asks two practical questions: (1) which controller gives the better nominal transient response, and (2) what trade-offs appear when a load torque is introduced?

Literature Review

Published work up to 2018 shows a consistent evolution from fixed-gain classical control toward rule-based and self-tuning control. Öztürk (2012) compared fuzzy and optimized PI strategies and highlighted the sensitivity of conventional gain selection to disturbances. Mohammed and Ali (2014) directly compared PID and FLC for a separately excited DC motor using MATLAB/Simulink and reported favorable fuzzy performance, particularly for nonlinear

conditions. Akbari-Hasanjani, Javadi, and Sabbaghi-Nadooshan (2015) extended the idea to self-tuning fuzzy PID control, in which the PID gains vary with operating error rather than remaining constant.

Fuzzy-controller research also examined controller structure and uncertainty. Hassani and Zarei (2015) used interval type-2 fuzzy logic for DC motor speed regulation and found that handling uncertainty explicitly can improve disturbance performance. Demidova, Kuzin, and Lukichev (2016) compared common fuzzy-controller forms for DC drives and showed that membership-function and inference choices materially affect performance. Almatheel and Abdelrahman (2017) again compared PID and Mamdani FLC and observed that fuzzy design is more involved, but can offer better nonlinear characteristics.

By 2018, research increasingly focused on self-tuning and anti-windup fuzzy-PID structures. Sim et al. (2018) reported that self-tuned fuzzy PID is less sensitive to parameter variation than conventional PID, while Huang, Wang, and Fang (2018) combined fuzzy self-tuning with anti-windup action for brushless DC speed control. These studies motivate a controlled baseline comparison: before hybrid or adaptive extensions are added, PID and FLC should be evaluated under identical conditions and with transparent performance indices.

Table 1. Literature findings used to define the comparison methodology.

Study	Controller focus	Main methodological implication
Öztürk (2012)	Fuzzy vs. optimized PI	Gain sensitivity and disturbance behavior must be compared.
Mohammed & Ali (2014)	PID vs. FLC	Use identical motor model and load/no-load tests.
Akbari-Hasanjani et al. (2015)	Self-tuning fuzzy PID	Fixed PID gains may be inadequate across operating points.
Hassani & Zarei (2015)	Type-2 FLC	Uncertainty handling is a key fuzzy-control advantage.
Demidova et al. (2016)	Fuzzy controller variants	Membership and rule design affect transient response.
Almatheel & Abdelrahman (2017)	PID vs. Mamdani FLC	FLC may improve nonlinear response but requires more design effort.
Sim et al. (2018)	Conventional vs. fuzzy PID	Self-tuning improves robustness to parameter variation.

Methodology

The methodology consists of five sequential stages: motor modeling, PID design, fuzzy-controller design, common simulation tests, and calculation of performance indices. Figure 1 summarizes the workflow. No controller is allowed a different plant model, reference command, supply limit, simulation interval, or disturbance magnitude.

1. DC Motor Mathematical Model

A separately excited armature-controlled DC motor is represented by the standard electrical and mechanical equations. The armature circuit and rotor dynamics are:

$$V_a(t) = R_a i_a(t) + L_a \frac{di_a(t)}{dt} + K_e \omega(t)$$

$$J \frac{d\omega(t)}{dt} + B\omega(t) = K_t i_a(t) - T^L(t)$$

where V_a is armature voltage, i_a is armature current, ω is angular speed, T^L is load torque, R_a and L_a are armature resistance and inductance, J is rotor/load inertia, B is viscous friction, and K_e and K_t are the back-emf and torque constants. Eliminating armature current gives the transfer function from voltage to speed:

$G(s) = \omega(s)/V_a(s) = K_t / [(L_a s + R_a)(J s + B) + K_e K_t]$. For the numerical illustration, $R_a = 1 \Omega$, $L_a = 0.5 \text{ H}$, $J = 0.01 \text{ kg}\cdot\text{m}^2$, $B = 0.01 \text{ N}\cdot\text{m}\cdot\text{s}/\text{rad}$, and $K_e = K_t = 0.1$. The command speed is 100 rad/s and the drive voltage is limited to $0\text{--}24 \text{ V}$. A $0.05 \text{ N}\cdot\text{m}$ load torque is applied at $t = 4 \text{ s}$ during an 8 s simulation.



Figure 1. Common workflow for the PID-FLC comparison.

Table 2. Common simulation and controller settings.

Parameter	Value	Purpose
Reference speed	100 rad/s	Common set point
Armature voltage limit	0–24 V	Actuator saturation
Load disturbance	0.05 N·m at 4 s	Disturbance test
Simulation time step	0.002 s	Numerical integration
PID gains	$K_p=0.15$, $K_i=0.30$, $K_d=0.002$	Fixed-gain benchmark
FLC inputs	$e/100$, $\Delta e/150$	Normalized error signals
FLC rule base	$7 \times 7 = 49$ rules	NB to PB linguistic sets
FLC output scaling	20 V/s incremental	Voltage-command update

2. PID Controller

The PID controller generates the armature-voltage command from the speed error $e(t) = \omega_{\text{ref}} - \omega(t)$: $u(t) = K_p e(t) + K_i \int e(t) dt + K_d de(t)/dt$. The proportional term accelerates the response, the integral term removes persistent offset, and the derivative term adds damping. The selected gains are fixed throughout the tests. Voltage saturation is included, and conditional integration is used so that the integral term does not continue accumulating when the actuator is saturated in the same direction as the error. This anti-windup precaution makes the comparison more realistic and prevents an artificially poor PID response.

3. Fuzzy Logic Controller

The FLC is implemented as an incremental Mamdani-style controller. Its two inputs are normalized speed error e and change of error Δe . Each input is partitioned into seven symmetric triangular linguistic sets: negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), and positive big (PB). The rule base contains 49 IF-THEN rules. Rules increase the voltage rapidly when a large positive error exists, decrease it for negative error, and use the change-of-error signal to reduce control action as the speed approaches the reference. A weighted centroid/singleton equivalent is used for defuzzification, and the result updates the armature-voltage command incrementally. This structure retains the main fuzzy-control advantage identified in earlier DC-

drive studies: the control law is expressed through qualitative error behavior rather than an exact inverse model (Mohammed & Ali, 2014; Demidova et al., 2016).

4. Test Procedure and Performance Indices

Step 1: initialize the motor at zero speed and zero current. Step 2: apply a 100 rad/s reference to both controllers at $t=0$. Step 3: enforce the same 24 V actuator limit. Step 4: at $t=4 \text{ s}$ applies a $0.05 \text{ N}\cdot\text{m}$ load torque without retuning either controller. Step 5: record motor speed and control voltage until $t=8 \text{ s}$. Step 6: compute the performance indices from the recorded speed traces.

Rise time is measured from 10% to 90% of the reference. Settling time is the earliest time after which the pre-disturbance response remains within $\pm 2\%$ of the reference. Maximum overshoot is the largest speed excursion above the set point expressed as a percentage. Steady-state error is evaluated immediately before the disturbance, and load-deviation percentage is the maximum absolute post-disturbance speed deviation from 100 rad/s . These indices are chosen because they capture speed, smoothness, precision, and disturbance behavior without favoring either controller architecture.

Results

Figure 2 shows the simulated speed responses obtained from the common motor model. The PID controller accelerates the motor more quickly, but its fixed gains produce a visible overshoot.

The fuzzy controller increases voltage more conservatively during the large-error phase and reduces its command as the error derivative indicates that the set point is being approached.

As a result, FLC rise time is longer, but the trajectory is smoother and enters the $\pm 2\%$ settling band earlier.

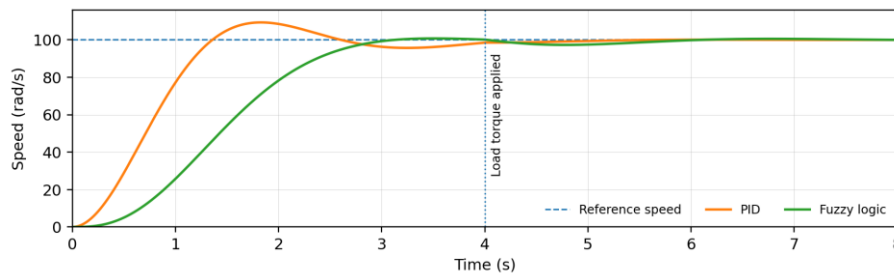


Figure 2. Representative PID and fuzzy-logic speed responses; load torque is applied at 4 s.

Table 3. Comparative time-domain results for identical test conditions.

Performance index	PID	Fuzzy logic	Interpretation
Rise time (10–90%)	0.898 s	1.712 s	PID reaches 90% faster.
Maximum overshoot	9.29%	0.73%	FLC strongly suppresses overshoot.
Settling time ($\pm 2\%$)	3.904 s	2.850 s	FLC settles earlier despite slower rise.
Pre-load steady-state error	1.52%	0.12%	FLC has smaller tracking offset.
Maximum load deviation	1.51%	2.73%	PID gives the smaller immediate load dip in this tuning.
Final speed at 8 s	99.97 rad/s	99.96 rad/s	Both recover close to the reference.

The numerical values illustrate a trade-off rather than a universal winner. Relative to the selected PID tuning, the FLC reduces overshoot from about 9.3% to below 1% and reduces settling time by roughly 27%. Its pre-load steady-state error is also much smaller. Conversely, the PID has approximately half the rise time and shows a smaller immediate speed deviation when the specified load torque is applied. These outcomes are consistent with the general literature: fuzzy rules can improve smooth nonlinear response, but results depend on scaling factors, membership design, and rule strength, while PID performance depends strongly on gain tuning (Ang et al., 2005; Hassani & Zarei, 2015).

Conclusion and Discussion

The comparative methodology demonstrates why PID and fuzzy logic controllers should be judged under the same motor and disturbance conditions. The PID controller is attractive because it is compact, computationally inexpensive, familiar to industrial engineers, and capable of a very rapid nominal response when gains are well chosen. Its principal weakness is that the three gains remain fixed even when the motor operating point, friction, inertia, or load changes. This limitation has motivated self-tuning fuzzy-PID and other adaptive extensions reported before 2018 (Akbari-Hasanjani et al., 2015; Sim et al., 2018). The fuzzy controller trades some initial response speed for a

smoother transient. In the present numerical case, it produced far less overshoot, an earlier settling time, and a lower pre-disturbance tracking error. Its rule base also provides a natural mechanism for modifying control action according to both error magnitude and error trend. However, fuzzy control is not automatically superior. Membership functions, normalization ranges, rule consequents, and output scaling must be selected carefully, and a controller tuned for low overshoot may react more slowly to a sudden load torque. The observed larger immediate load dip for FLC is therefore an important result rather than an anomaly; it shows that a fair comparison must report multiple performance indices instead of presenting only the most favorable metric. For applications such as low-cost constant-speed drives with a well-characterized plant, a tuned PID remains a strong choice. For drives exposed to nonlinearities, uncertain parameters, wide operating ranges, or where overshoot is undesirable, fuzzy logic offers useful design flexibility. A practical next step would be to compare both controllers on hardware using encoder feedback and a PWM converter, then repeat the tests after $\pm 20\%$ changes in inertia, armature resistance, and load torque. Hybrid fuzzy-PID control could also be evaluated, but it should be treated as a third controller rather than used to blur the baseline PID–FLC comparison. Overall, the methodology supports a balanced

conclusion: PID provides simpler and faster nominal control, while fuzzy logic can provide smoother settling and better tracking quality when its rule base is appropriately designed.

References

- Ziegler, J. G., & Nichols, N. B. (1942). Optimum settings for automatic controllers. *Transactions of the ASME*, 64(8), 759–768. <https://doi.org/10.1115/1.4019264>
- Zadeh, L. A. (1965). Fuzzy sets. *Information and Control*, 8(3), 338–353. [https://doi.org/10.1016/S0019-9958\(65\)90241-X](https://doi.org/10.1016/S0019-9958(65)90241-X)
- Mamdani, E. H., & Assilian, S. (1975). An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Man-Machine Studies*, 7(1), 1–13. [https://doi.org/10.1016/S0020-7373\(75\)80002-2](https://doi.org/10.1016/S0020-7373(75)80002-2)
- Ang, K. H., Chong, G., & Li, Y. (2005). PID control system analysis, design, and technology. *IEEE Transactions on Control Systems Technology*, 13(4), 559–576. <https://doi.org/10.1109/TCST.2005.847331>
- Öztürk, N. (2012). Speed control for DC motor drive based on fuzzy and genetic PI controller – A comparative study. *Elektronika ir Elektrotechnika*, 123(7), 43–48. <https://doi.org/10.5755/j01.eee.123.7.783>
- Mohammed, O. O. A., & Ali, A. T. (2014). Comparative study of PID and fuzzy controllers for speed control of DC motor. *International Journal of Innovative Research in Science, Engineering and Technology*, 3(9), 16104–16110. <https://doi.org/10.15680/IJIRSET.2014.0309045>
- Akbari-Hasanjani, R., Javadi, S., & Sabbaghi-Nadooshan, R. (2015). DC motor speed control by self-tuning fuzzy PID algorithm. *Transactions of the Institute of Measurement and Control*, 37(2), 164–176. <https://doi.org/10.1177/0142331214535619>
- Hassani, H., & Zarei, J. (2015). Interval type-2 fuzzy logic controller design for the speed control of DC motors. *Systems Science & Control Engineering*, 3(1), 266–273. <https://doi.org/10.1080/21642583.2015.1013644>
- Demidova, G. L., Kuzin, A. Y., & Lukichev, D. V. (2016). Application features of fuzzy controllers on example of DC motor speed control. *Scientific and Technical Journal of Information Technologies, Mechanics and Optics*, 16(5), 872–878. <https://doi.org/10.17586/2226-1494-2016-16-5-872-878>
- Almatheel, Y. A., & Abdelrahman, A. (2017). Speed control of DC motor using fuzzy logic controller. In 2017 International Conference on Communication, Control, Computing and Electronics Engineering (ICCCCEE). IEEE. <https://doi.org/10.1109/ICCCCEE.2017.7867673>
- Sim, S. Y., Goh, H. H., Utomo, W. M., Buswig, Y. M. Y., Lim, A. J. M. S., Goh, K. C., Zin, N. M., Cham, C. L., & Ahmad, M. Y. (2018). A comparative study of conventional PID and intelligent PID for DC motor speed control. *Journal of Fundamental and Applied Sciences*, 10(5S), 282–297. <https://doi.org/10.4314/jfas.v10i5s.25>
- Huang, J., Wang, J., & Fang, H. (2018). An anti-windup self-tuning fuzzy PID controller for speed control of brushless DC motor. *Automatika*, 59(3–4), 321–335. <https://doi.org/10.1080/00051144.2018.1423724>